

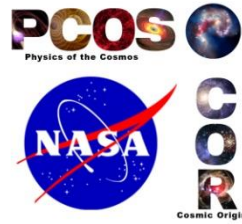
FUV Reflectance of recently prepared Al protected with AlF_3

COR Program Technology Development

By

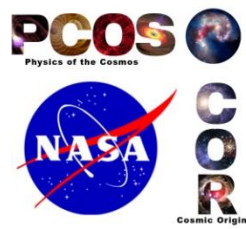
Manuel Quijada/GSFC Code 551

Outline



- Motivation
- Project Objectives
- Leveraging Successes:
 - Acquisition of new FUV McPherson spectrometer
 - Transfer of vacuum coated to our branch
- Recent Technical achievements:
 - Al/MgF₂/LiF/AlF₃ Coating processes
 - AFM results
- Conclusions
- Acknowledgements

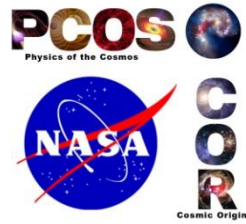
Enhanced UV Coating Applications



- Distant and faint objects are typically searched for in cosmic origin studies:
 - Origin of large scale structure
 - The formation, evolution, and age of galaxies
 - The origin of stellar and planetary systems
- Astronomical observations in the Far Ultraviolet (FUV) spectral region are some of the more challenging
- Very limited option of reflecting coatings to use at FUV wavelengths:
 - Modest reflectivity offered by those coatings
 - Al+MgF₂ [typically 82% at Lyman-alpha, 1216 Å) that are used on reflecting surfaces of FUV instrumentation
- Improved reflective coatings for optics at FUV could yield dramatically more sensitive instruments .
- Permit more instrument design freedom



Large UV/Optical/Infrared (LUVOIR) Decadal Mission Concept Study



LUVOIR Science Technology Definition Team (STDT) met at GSFC on 8/18-19/2016

Proposed instruments suite:

1. Optical / NIR Coronagraph:
 - a) Capable of imaging and detecting bio-signatures on Earth-like planets around sun-like stars.
 - b) Requires as broad a bandpass as possible (notionally 400 nm - 1.8 μ m, to be revised)
 - c) Spectral resolving power of $R \sim 200$
 - d) Possibly to include polarimetry
2. UV Imager & Spectrograph:
 - a) High-resolution point-spectroscopy ($R \sim 1,000$ - 200,000)
 - b) Multi-object spectroscopy capability (possibly including an IFS/IFU)
 - c) UV Imaging with a minimum 1 arcmin x 1 arcmin FOV
3. Wide-field Optical / NIR Imager:
 - a) 4-6 arcmin x 4-6 arcmin FOV
 - b) Individual filter bands TBD, possibly to include a grism
 - c) Possibly to include sub-microarcsecond astrometry capability
4. Multi-resolution Optical / NIR Spectrograph:
 - a) Point-detector spectrometer, possibly to include an IFU/IFS
 - b) $R \sim 100,000$ for template matching & solar system science
 - c) $R \sim 2,000$ for transit spectroscopy
 - d) Possibly to include high-precision 1 cm/s radial velocity measurement capability
 - e) Broad-wavelength coverage in a single shot, as red as possible (at least 3.5 μ m for transit spectroscopy)

Investment in developing high throughput FUV coatings is an **enabling** technology for #2

Project Objectives

- Use improved deposition processes to develop high performance mirrors in the Ultraviolet spectral range
- Specific tasks:
 - Research low-absorption materials to design and produced dielectric coatings in the FUV
 - Improve FUV mirror reflectance of aluminum mirrors over-coated with MgF_2 and LiF in a large 2-meter UHV chamber
 - Coat variety of substrates using different materials covering the 90-170 nm spectral range.
- Key challenges:
 - Achieving high reflectivity (> 90-95%) in the 90 to 250 nm range requires absorption-free optical coatings
 - Low stress strong adhesion in coatings
 - Environmentally stable coatings
 - Precise & accurate techniques
 - Scaling coatings to large diameter (1+ meter class) mirror substrates

Leveraging Resources for Success

- Resource acquisition for coating testing & development
 - Acquisition of new FUV McPherson spectrophotometer for measuring transmittance/reflectance in the 90-170 nm (\$225k).
 - Acquired from another branch a “turn key” Physical Vapor Deposition Kurt J. Lesker (Model # PVD 75).
 - Ongoing coating development activities of Al+AlF₃ protected coatings (GSFC FY16 IRAD (PI: Javier Del Hoyo)
 - Submitted APRA proposal entitled “***Mission Enabling LUNAR Astronomy through Enhanced Coatings***”. Proposal was peer-reviewed and deemed “**SELECTABLE**”.

Acquisition of New FUV spectrophotometer

Completed purchase & installation of new McPherson 225 spectrometer on May, 2016

General Specifications:

- Model 225 1m focal length, f/10/4
- Spectral range: 90-200 nm
- Automated T/R capability permits accurate and fast data acquisition
- Windowless H₂ purged source
- PMT tube detector with vacuum tight scintillator coated window for response from 30 nm to 200 nm.



Kurt Lesker Thin Film Deposition System

PVD 75™ PRO Line Thin Film Deposition System



Kurt J. Lesker®
Company

PROCESS EQUIPMENT™
DIVISION

Applications

- Designed for university, industrial, and government lab R&D thin film deposition
- OLED/PLED and organic electronics applications
- Photovoltaics and semiconductor devices
- Optics and decorative coatings
- Small batch production

Features

- Fully enclosed "zero" clean room footprint or optional open frame design
- Box 304 stainless steel chamber with aluminum door and large viewport
- Manual touch-screen or recipe-controlled, PC based process automation
- Turbomolecular or optional cryogenic high vacuum pumping

Process Modules

- Magnetron sputtering: RF, DC, Pulsed DC
- Electron beam evaporation
- Thermal evaporation
- Organic materials evaporation
- Ion source substrate cleaning or assisted deposition

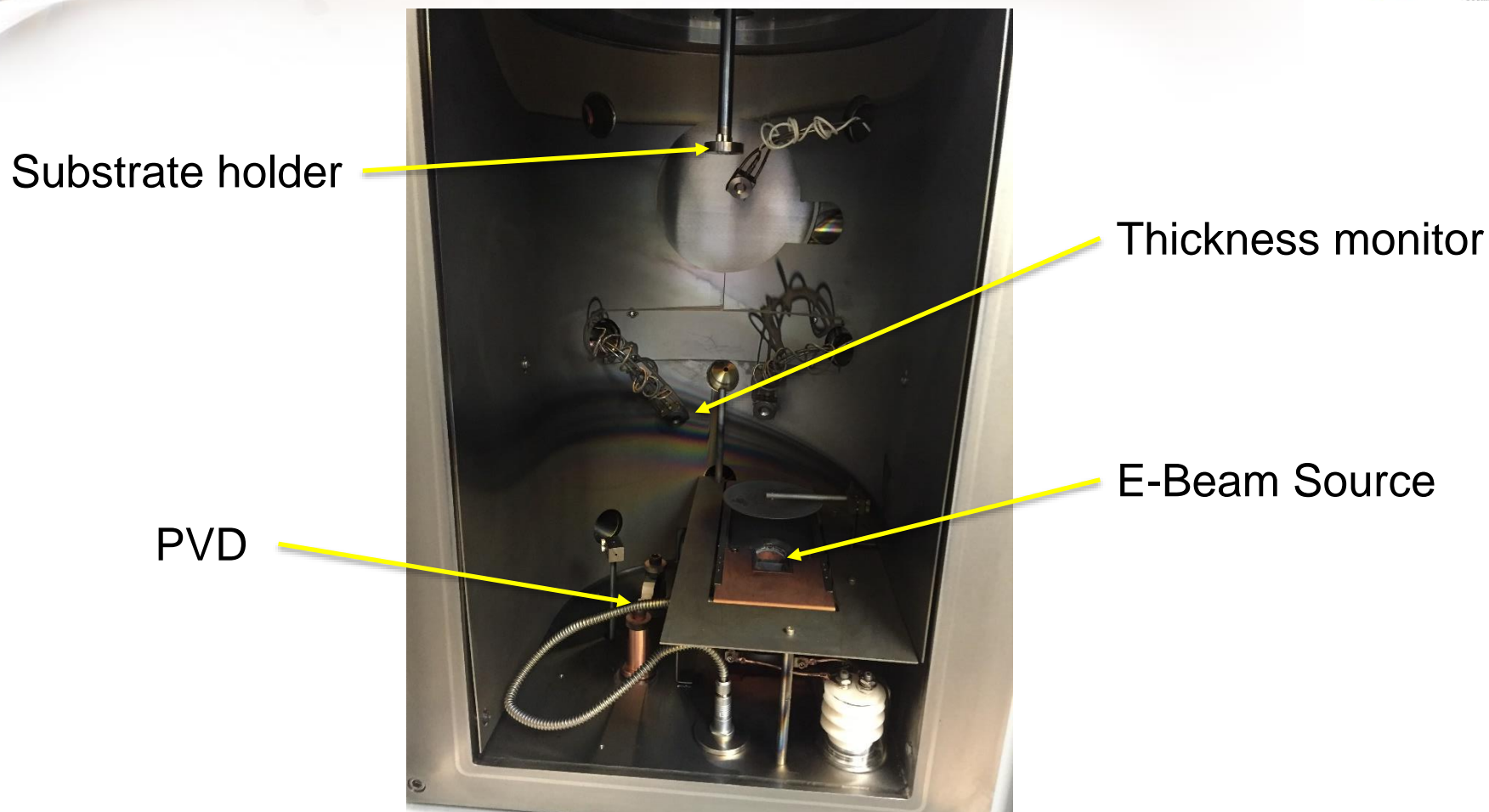
Options

- Substrate heating, cooling, or biasing
- Planetary substrate fixturing
- Upstream or downstream pressure control
- Film thickness control
- Substrate load lock
- On-site installation and training

www.lesker.com

- Took possession of a "turn-key" thin-film deposition system from another branch.
- Capability to perform test coatings (up to a few inches in diameter) for R & D purposes.
- Coating process includes Physical Vapor Deposition and Electron beam evaporation.

Inside PVD 75 Coating Chamber



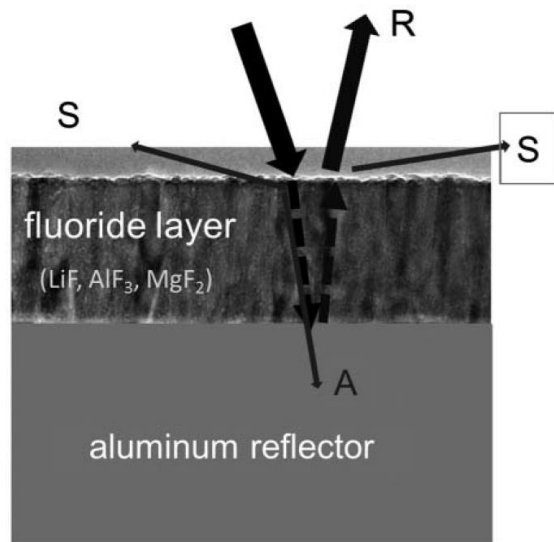
PVD 75 will be used primarily as thin-film R & D resource

Fluorides as Protection Layers

Using fluorides as protectors for Al:

(Wilbrandt *et.al.* Vol. 53 No. 4 App. Opt. 2014):

Absorption edges: 116 nm (MgF_2), 110 nm (AlF_3), and 104 nm (LiF)



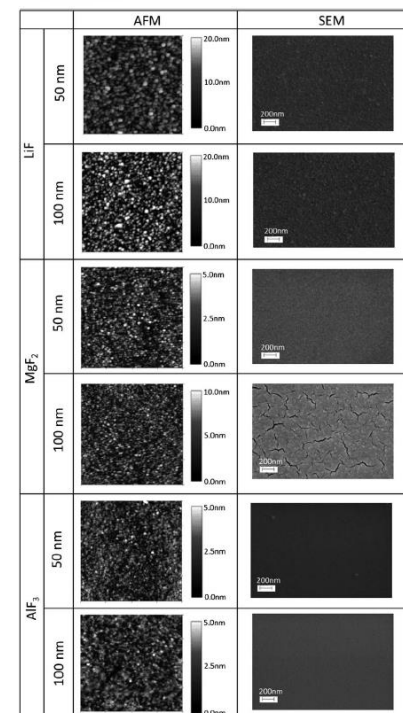
Optical Constants

$$R = 1 - A - S$$

Roughness

Overview of Roughness Values for Protected Aluminum Mirrors

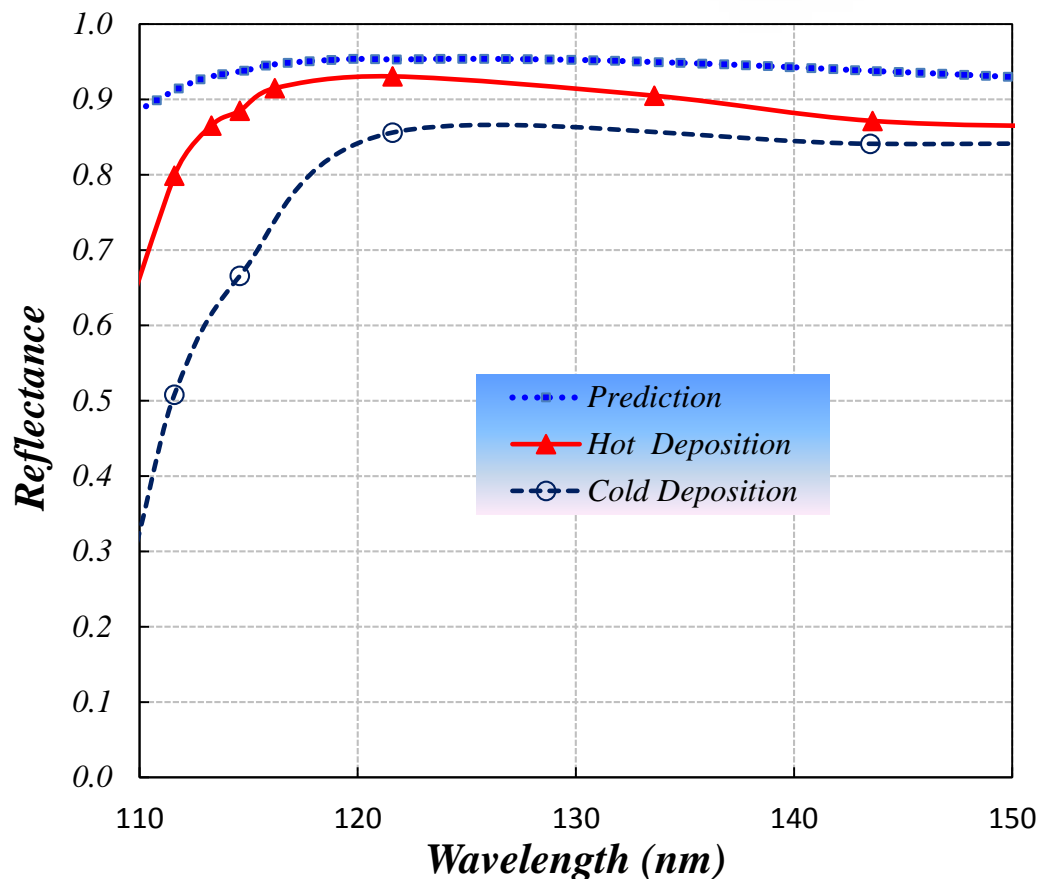
Type	Rate in nm/s	σ in Nanometer	
		1 μm	10 μm
Al+ AlF_3	0.2	1.34	1.38
	2.0	1.23	1.31
Al+LiF	0.2	5.81	4.69
	2.0	5.20	4.16
Al+ MgF_2	0.2	1.39	1.36
	2.0	1.70	1.51



- AlF_3 & MgF_2 exhibit the lowest (comparable) roughness.
- LiF films have significantly higher roughness.
- Surface roughness increases with layer thickness.
- Surface roughness decreases with increased deposition rate.

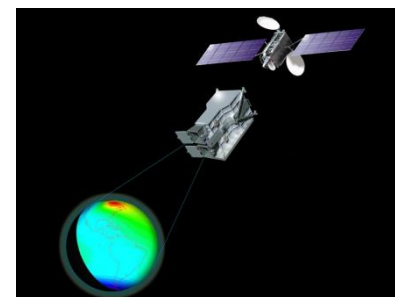
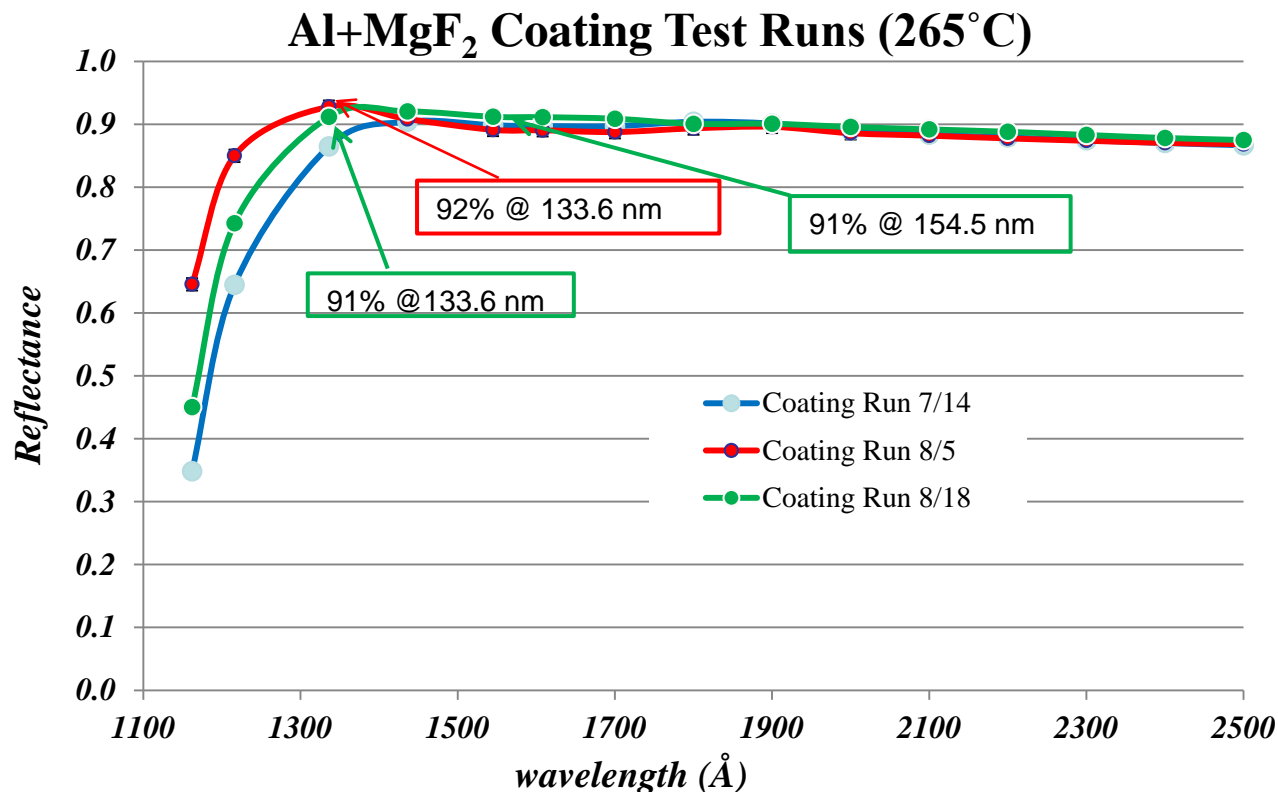
Al+MgF₂ Mirror FUV Performance

- Predicted vs. measured reflectance of bare Al and Al+MgF₂ reflectance (Al: 50.0 nm; MgF₂: 25.0nm)
- Enhanced performance is obtained by heating (~220 ° C) substrate during MgF₂ deposition
- Reflectance > 80% at $\lambda > 115.0$ nm



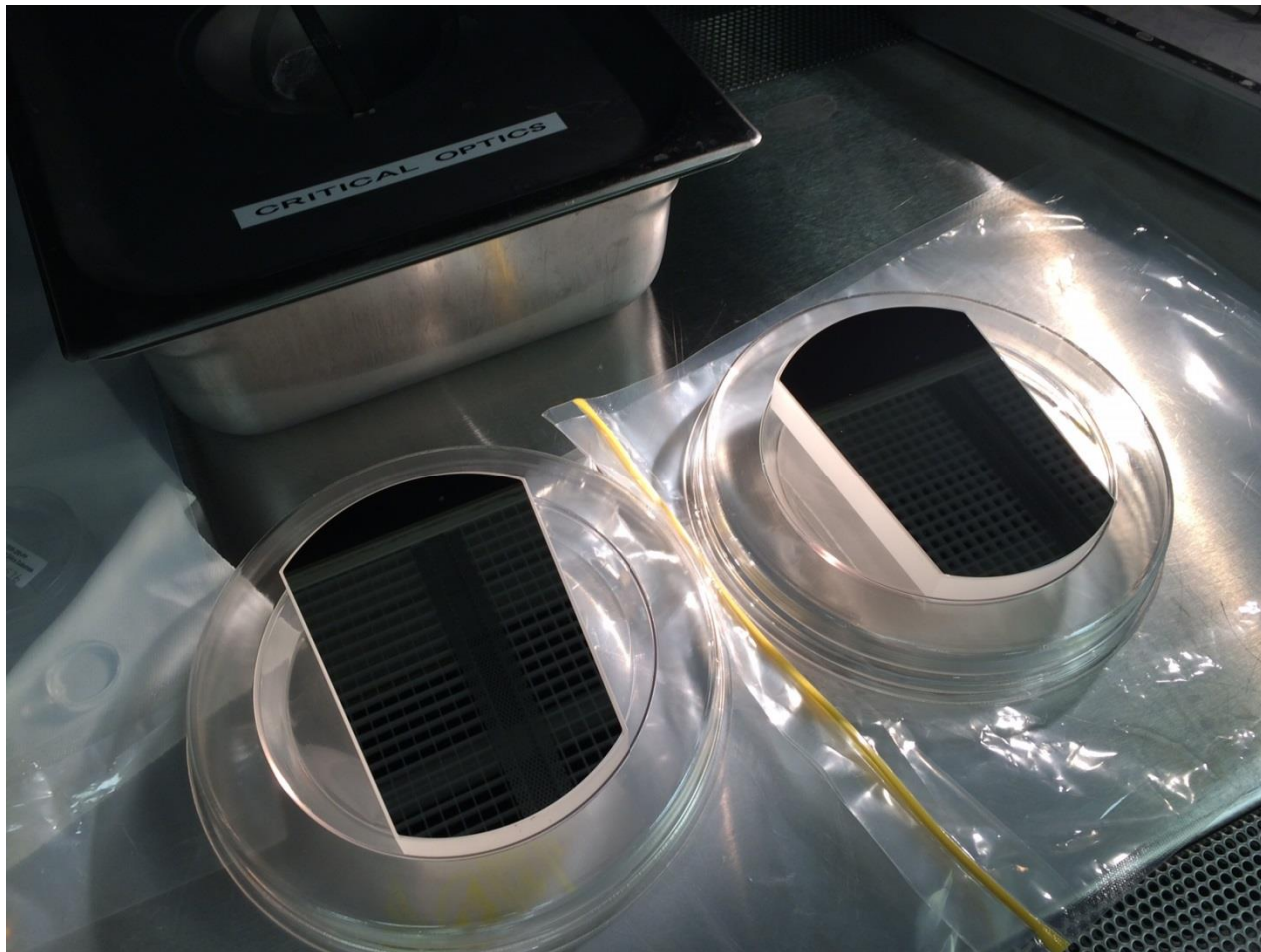
ICON/GOLD Coating Tasks

- ICON (Ionospheric Connection explorer): Study Earth's low-orbit ionosphere sun interactions
- GOLD (Global-scale Observations of the Limb and Disk) : Imager to map Earth's thermosphere & ionosphere

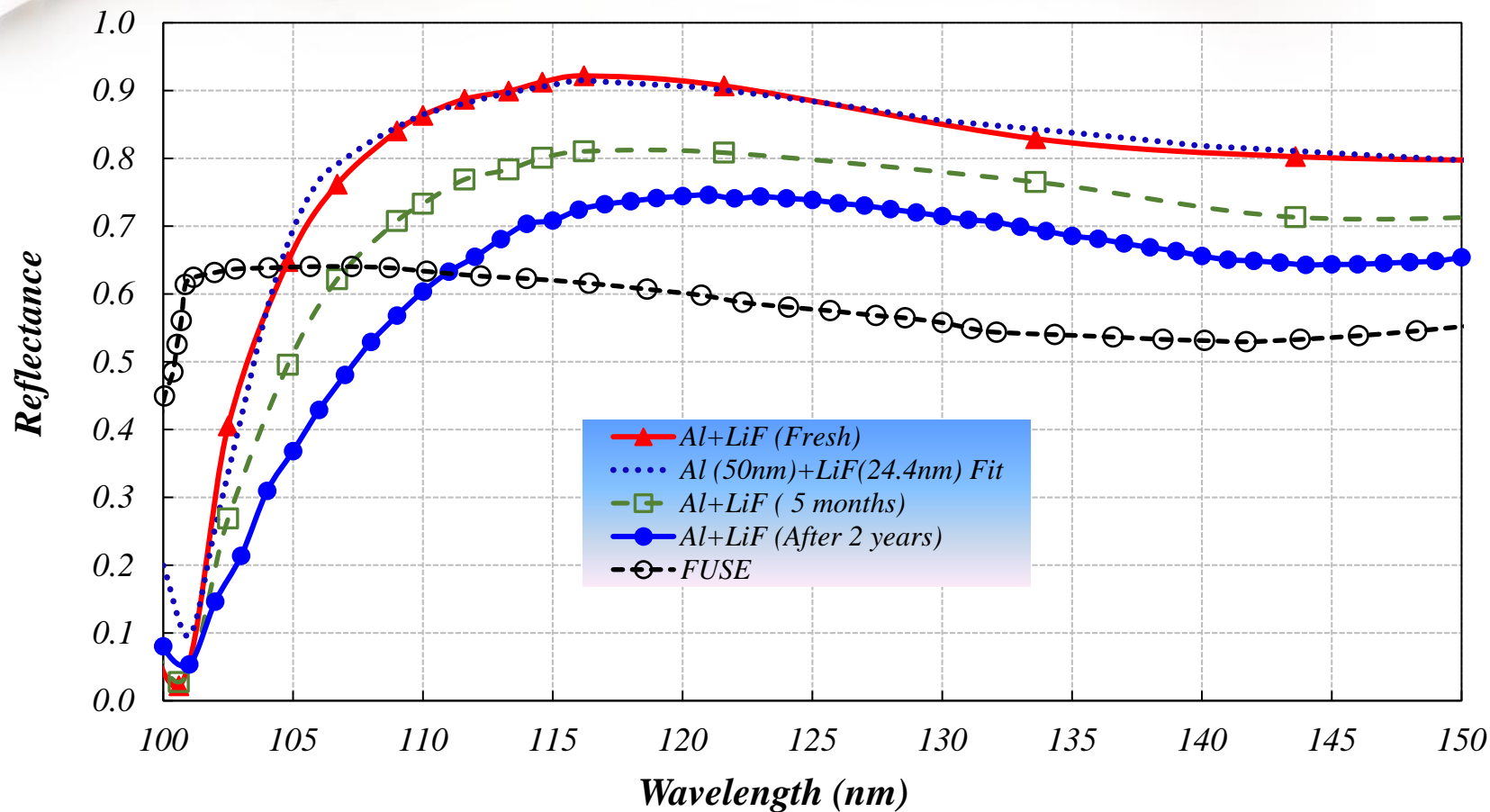


- A total of 12 optics ranging in size from 26 mm to 264 mm
- Coatings are optimized to produce reflectance over 90% in the 134-156 nm range

ICON Optics



Al+LiF Mirror FUV Performance



Coating recipe: Al (43nm, ambient)+LiF(8nm, ambient)+LiF(16.4nm, 250 ° C)

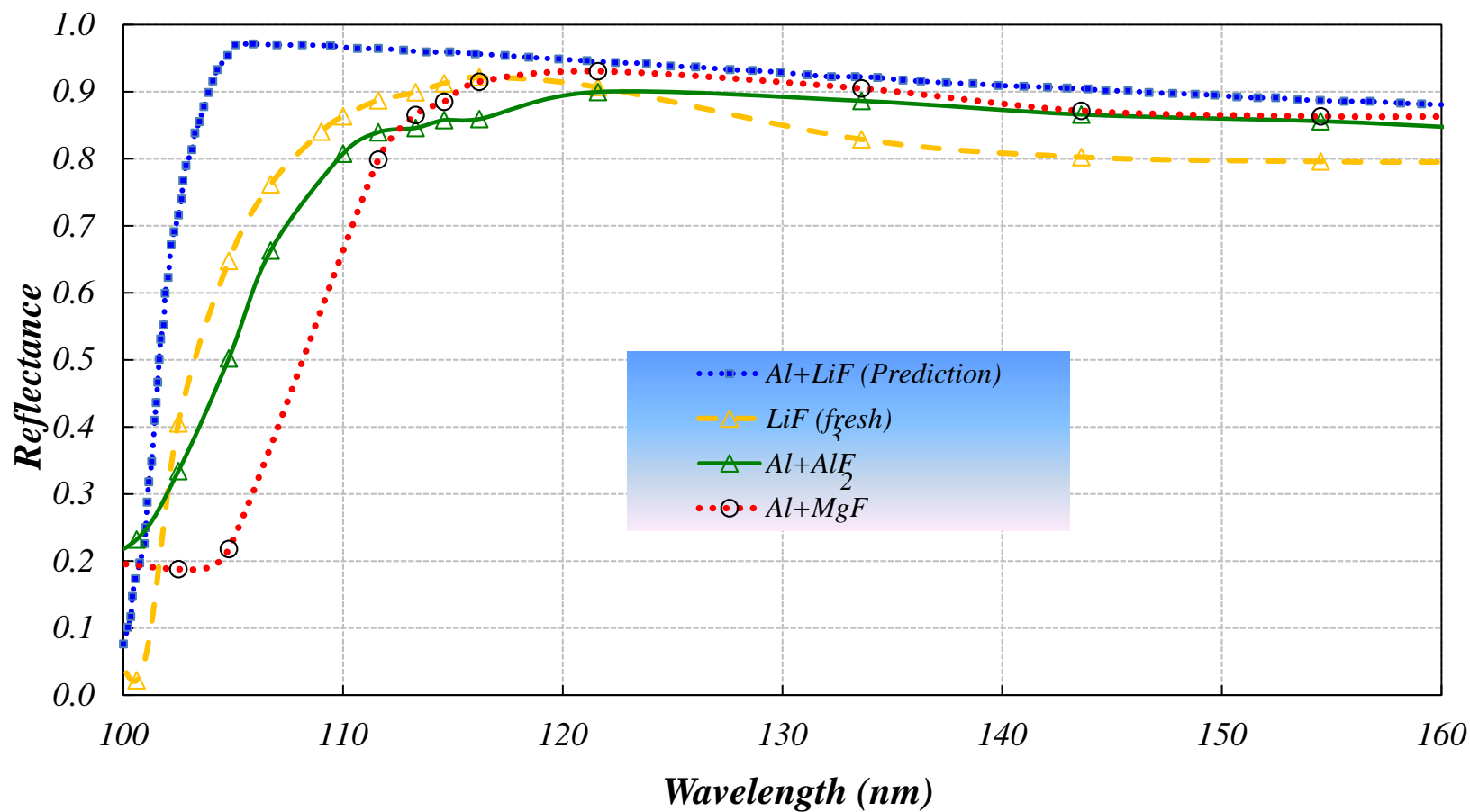
$R_{ave}(100-150nm)$: 59% (FUSE) 75% (LiF)

LiF has to be deposited to optimize the 100-121 nm spectral range

Al+AlF₃ as FUV Mirror Potential

- AlF₃ is another low-index fluoride with good transparency in the FUV
- Absorption edge is between MgF₂ and LiF (110 nm)
- Hydrophilic material
 - ✓ The affinity to bond, at a molecular level, with water.
 - ✓ Note: This is not the same as [hygroscopic](#), which is the ability of a substance to actively attract and [absorb water vapor in the air](#) without bonding
- Started to produce Al+AlF₃ test witness samples (to leverage success we have had with both MgF₂ and LiF)
- Goal is to produce test samples:
 - ✓ To enhance FUV reflectance
 - ✓ Environmentally stable

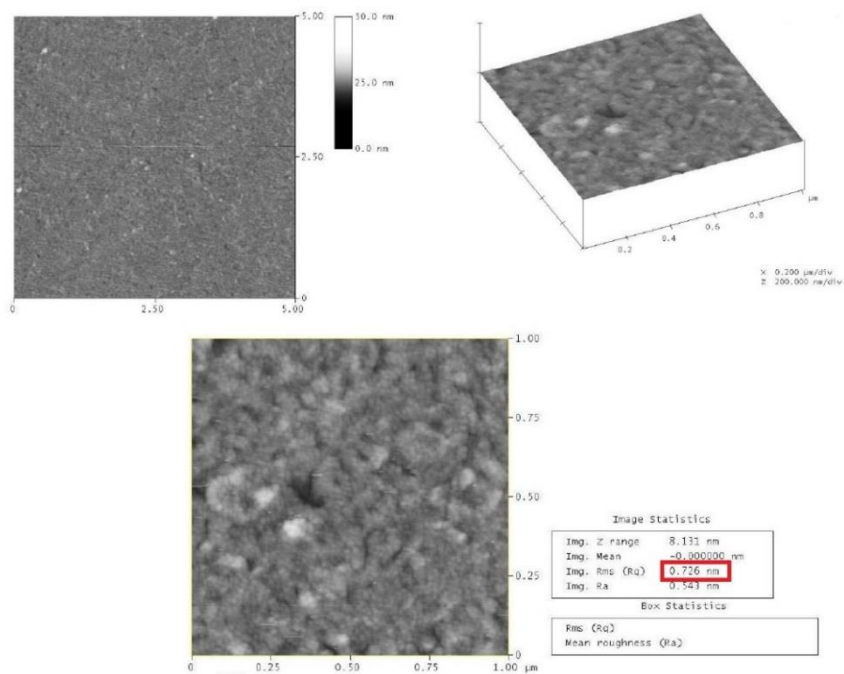
Al+LiF Mirror FUV Performance



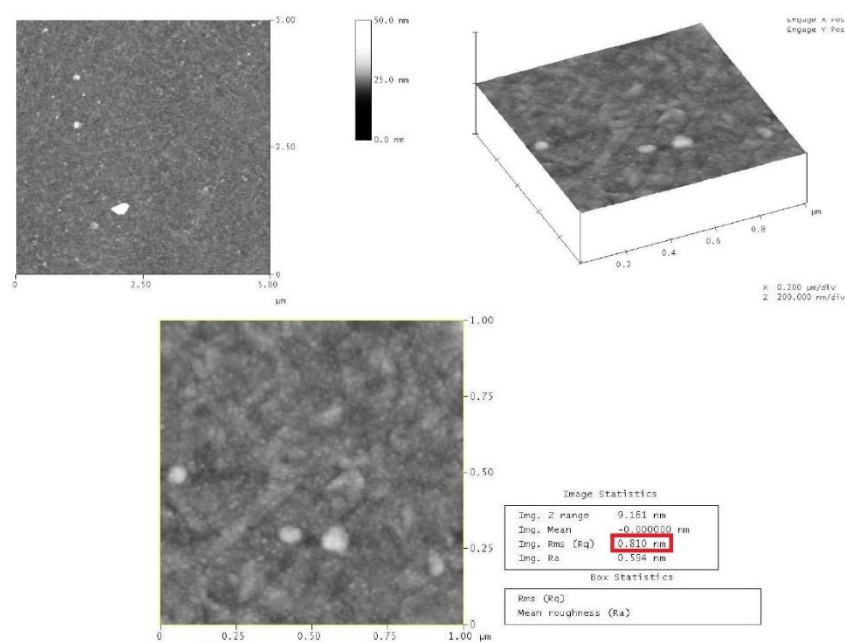
AlF3 thickness: 195 Å (Al: 600 Å)

Atomic Force Microscope Study

Al+MgF₂



Al+AlF₃

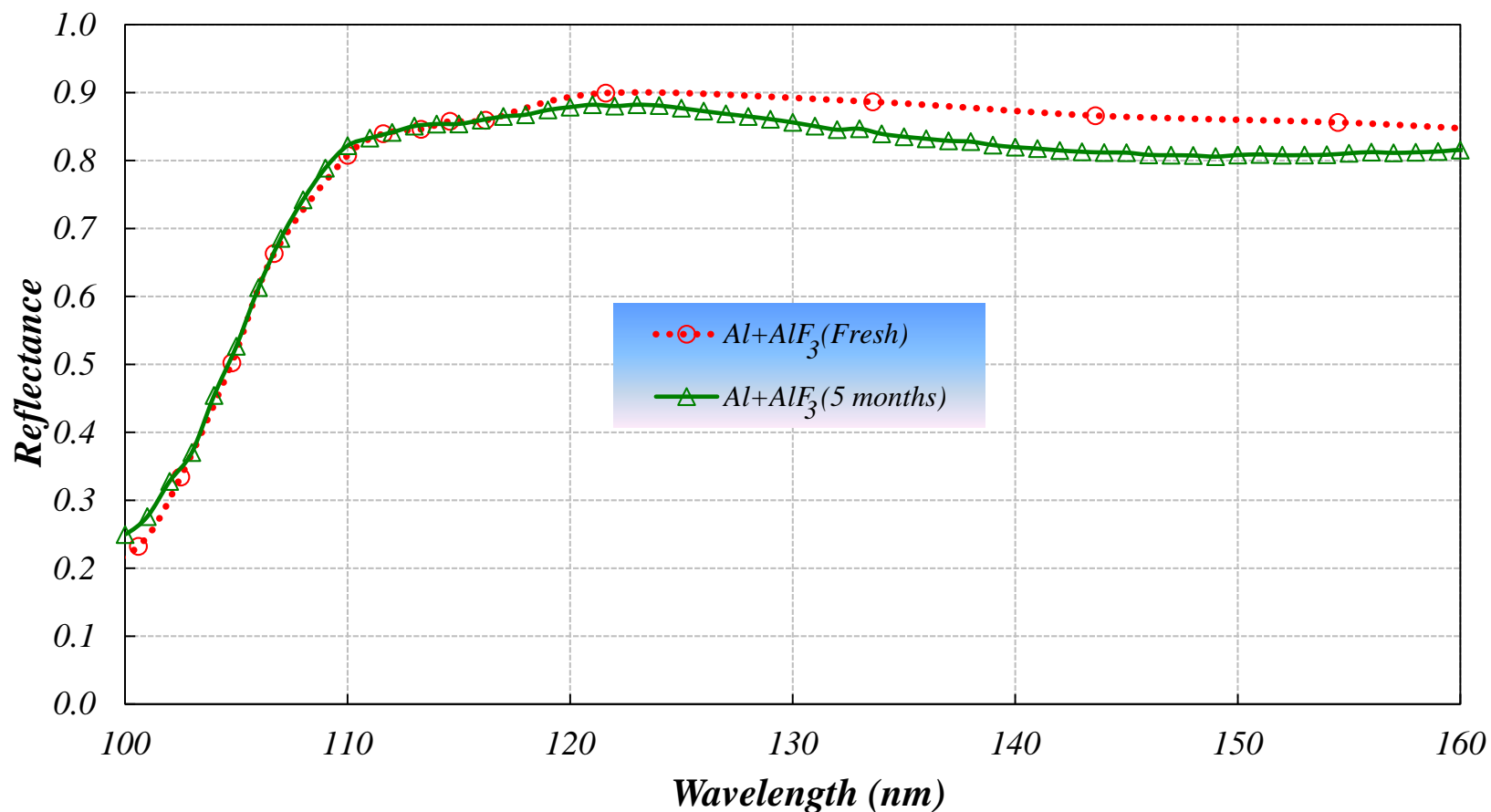


Al+MgF₂ → Rq (RMS) = 0.726 nm

Al+AlF₃ → Rq = 0.910 nm

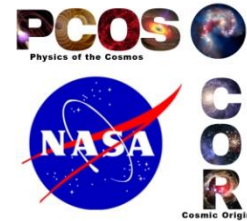
Results are 35 % (AlF₃) and 65% (MgF₂) lower than Wilbrandt *et al.*

Al+AlF₃ FUV Reflectance Durability



Witness sample appears stable when stored in ambient lab conditions

Conclusions



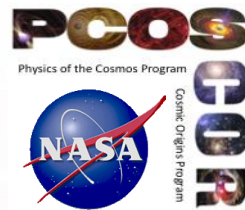
- Reported gains in FUV reflectivity of $\text{Al}+\text{MgF}_2$ and $\text{Al}+\text{LiF}$ mirrors by employing a 3-step process during PVD coating deposition of these materials.
- Applied enhanced FUV coating on ICON and GOLD projects.
- Recent acquisition of a new McPherson FUV spectrometer and transfer of a Kurt Lesker vacuum coater
- Successful demonstration of enhancement in FUV reflectance of $\text{Al}+\text{AlF}_3$ samples.
- Further coating development pending final funding outcome of new APRA proposal

Acknowledgement

Collaborators: Javier del Hoyo/551,
Felix Threat/551,
Ed Wollack/665,
Vivek Dwivedi/545
Ray Adomaitis (UMD)
Brian Fleming (U of CO)
Kevin Frances (U of CO)

Enhanced MgF_2 and LiF Over-coated Al Mirrors for FUV Space Astronomy

PI: Manuel A. Quijada/Code 551



Description and Objectives:

- Development of high reflectivity coatings to increase system throughput, particularly in the far-UV (FUV) spectral range
- Study other dielectric fluoride coatings and other deposition technologies such as Ion Beam Sputtering (IBS) that is expected to produce the nearest to ideal morphology optical thin film coatings and thus low scatter.

Key challenge/Innovation:

- Achieving high reflectivity (> 90-95%) in the 90 to 250 nm range
- Scaling up coatings to large diameter (1+meter) mirror substrates

Approach:

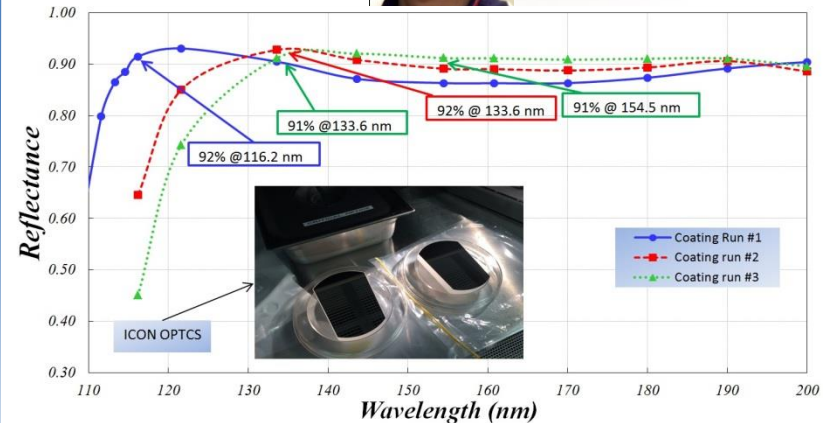
- Retrofit a 2 meter coating chamber with heaters/thermal shroud to perform Physical Vapor Depositions at high temperatures (200-300 C) to further improve performance of Al mirrors protected with either MgF_2 or LiF overcoats.
- Optimize deposition process of lanthanide trifluorides as high-index materials that when paired with either MgF_2 or LiF will enhance reflectance of Al mirrors at Lyman-alpha.
- Establish the IBS coating process to optimize deposition of MgF_2 and LiF with extremely low absorptions at FUV wavelengths.

Collaborators:

- Javier del Hoyo, Steve Rice and Felix Threat (551)
- Jeff Kruk and Charles Bowers (665)

Development Period:

Oct. 1, 2011 – Sept. 30th, 2014



Various test runs to produce coatings with over 90% reflectance for ICON optics in FUV

Accomplishments:

- Performed end-to-end testing of the 3-step Physical Vapor Deposition (PVD) coating process in 2 meter chamber to enable 1+meter class mirrors with either $\text{Al}+\text{MgF}_2$ or $\text{Al}+\text{LiF}$ coatings for FUV applications
- Completed characterization of lanthanide trifluorides (GdF_3 and LuF_3) to pair them with low-index MgF_2 layers to produce narrow-bands dielectric reflectors at FUV wavelengths
- Production of mirrors with reflectance over 90% in FUV for ICON and GOLD projects.

Application:

- Application of these enhanced mirror coating technology will enable FUV missions to investigate the formation and history of planets, stars, galaxies and cosmic structure, and how the elements of life in the Universe arose.

$TRL_{in} = 3$ $TRL_{current} = 4$ $TRL_{target} = 4$

Backup slides

GSFC Coating Facilities

- Deposition methods: PVD, IBS, and RF Magnetron Sputtering
- Coatings produced: Al, MgF₂, LiF, SiO_x, GdF₃, LuF₃, Al₂O₃, Ag, Cr, Y₂O₃, SiC, B₄C.

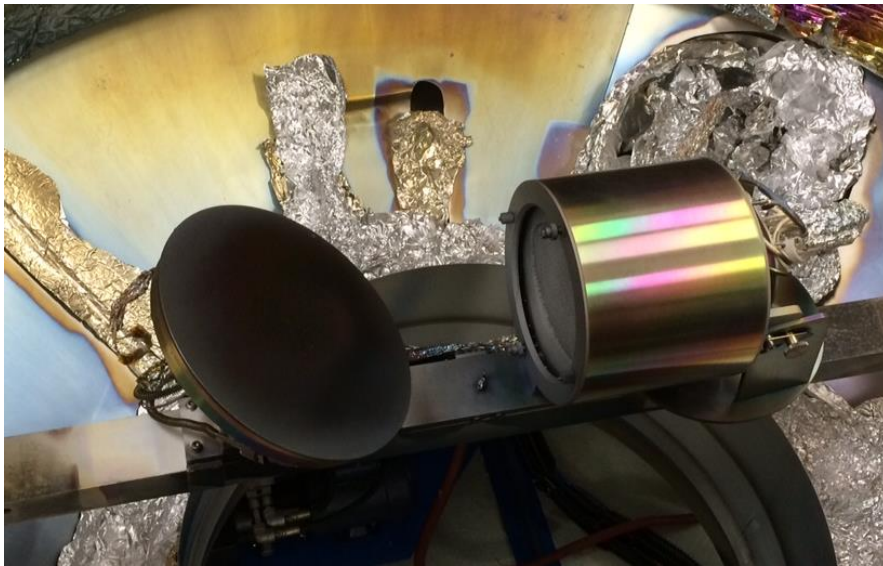


PVD UHV coating chamber
(1-meter diameter)

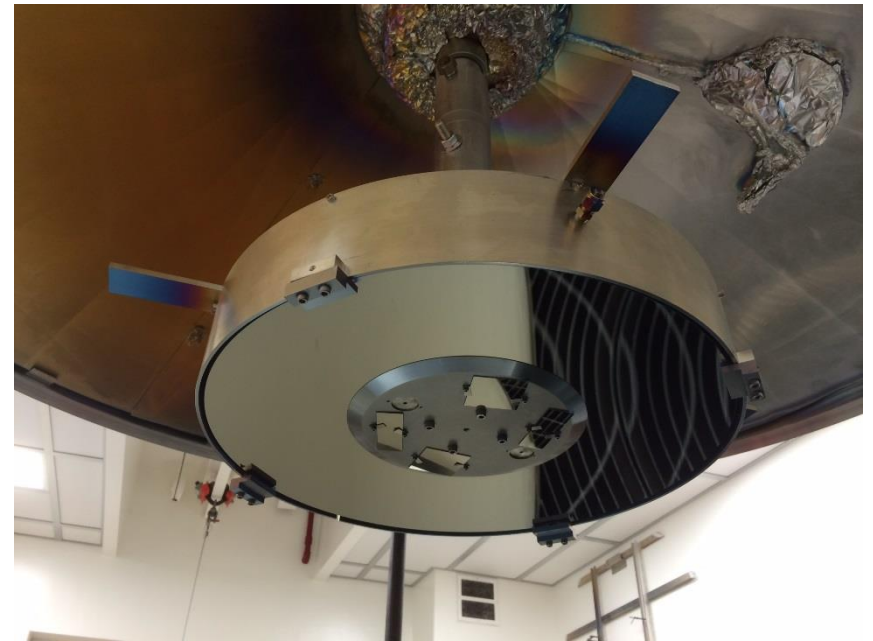


PVD/ IBS UHV coating chamber
(2-meter diameter)

2-Meter Diameter UHV Chamber



Ion Beam Sputtering Setup



Chamber top Cover with recently coated mirror substrate.

Missions supported:

ICON, Astronomical Observatory (OAO) & Ultraviolet Explorer (IUE)
FUSE, HST (COSTAR, GHRS & COS), and a number of sounder rocket missions

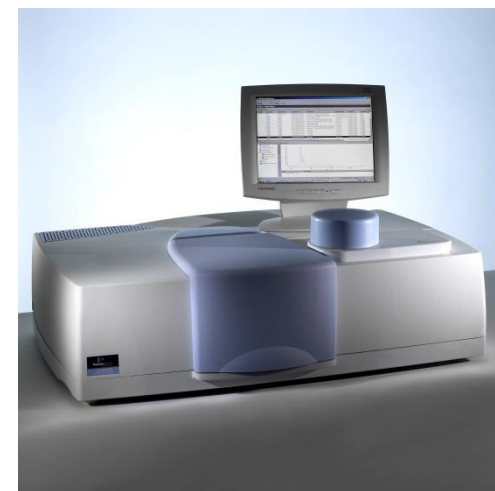
Optical Characterization: $T(\lambda)$, $R(\lambda)$

ACTON VUV Spectrometer



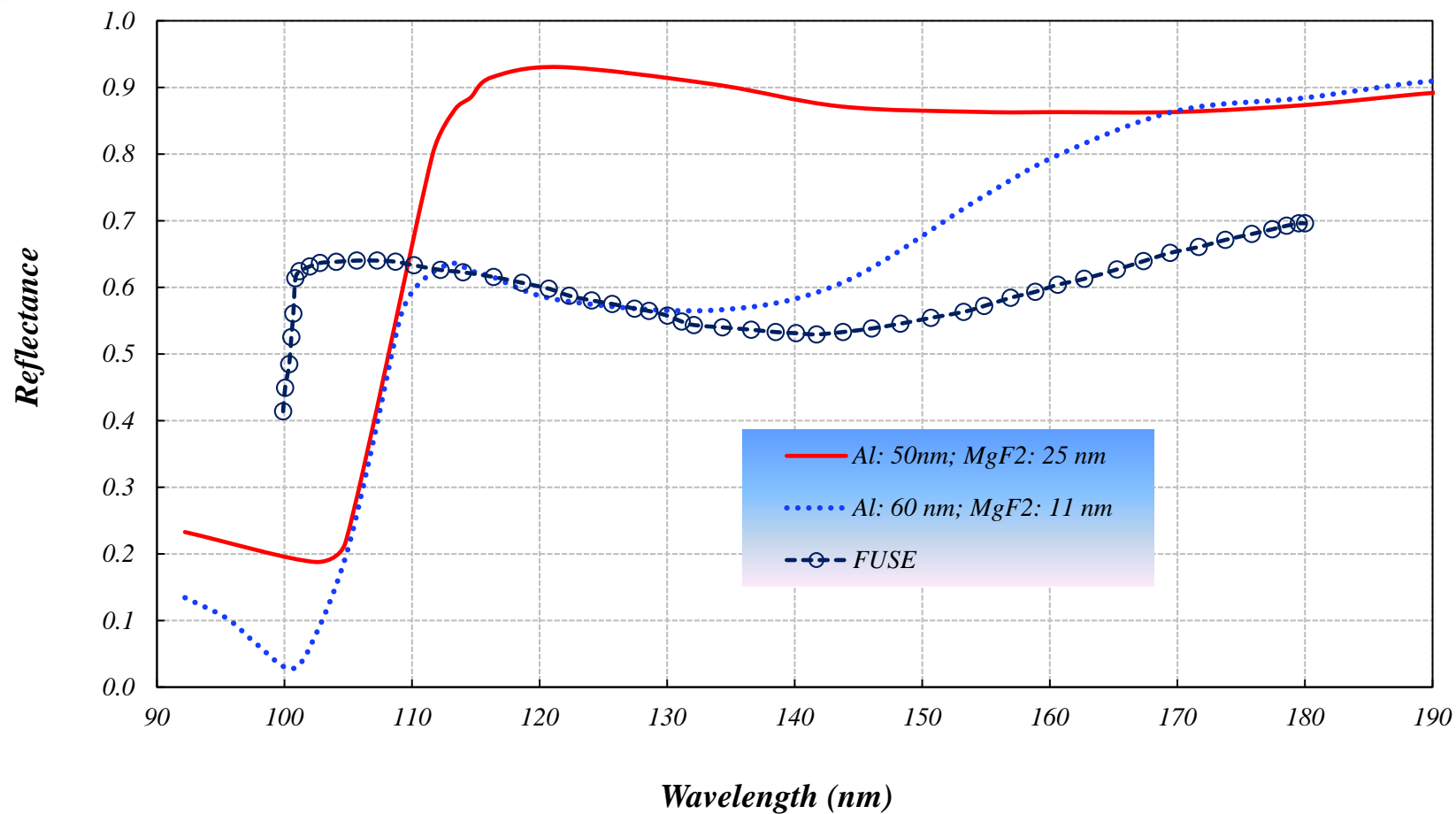
- Spectral range: 30-300 nm
- Source: Windowless H₂-purged source (H₂ emission lines between 90 nm and 160 nm and a continuum at higher nm and 160 nm and a continuum at higher nm)
- Detector: PMT with fluorescence coating

Perkin Elmer Lambda 950

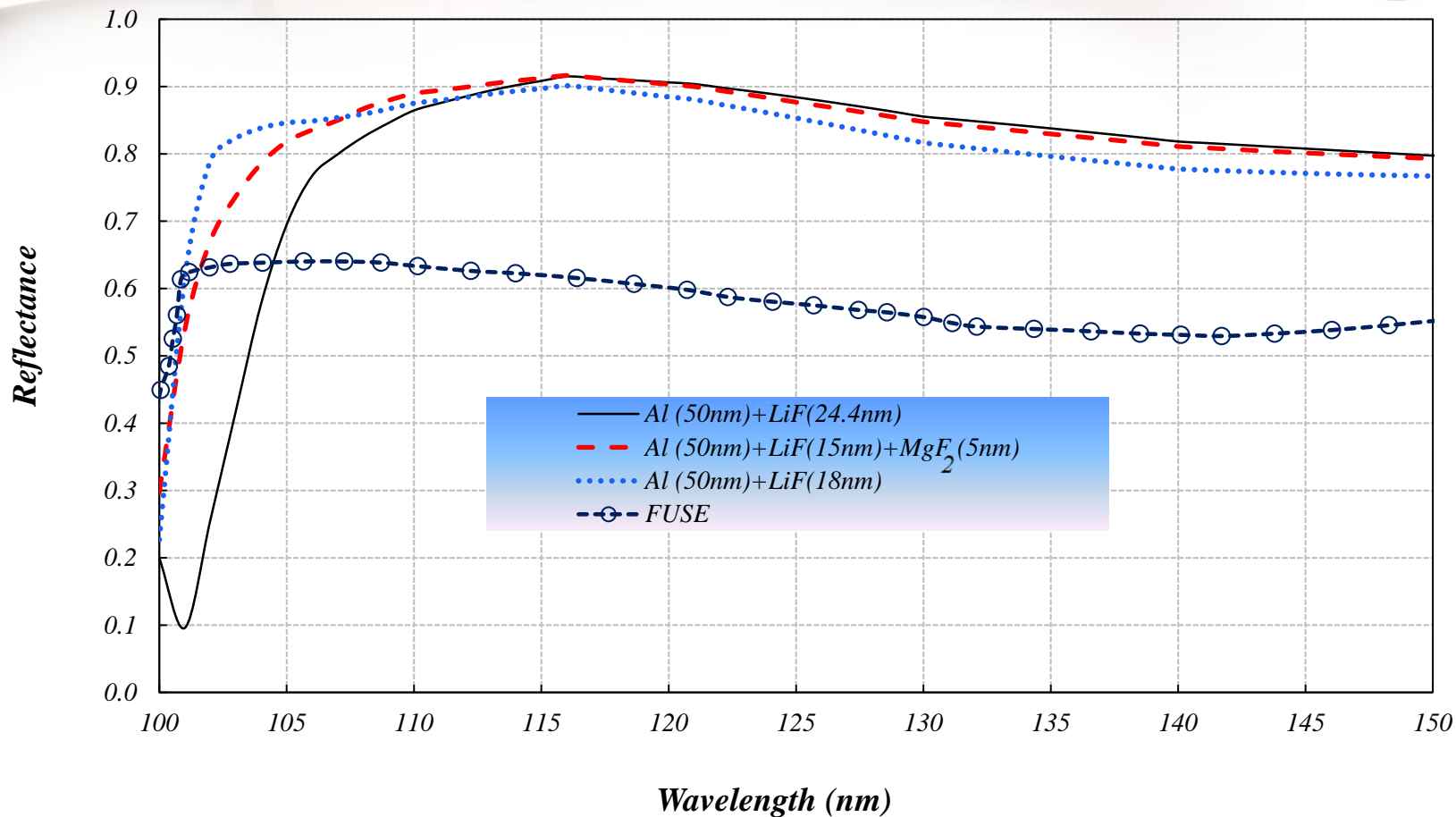


Spectral range: 190-2500 nm
Universal Reflectance Accessory

Thin MgF₂ Overcoat



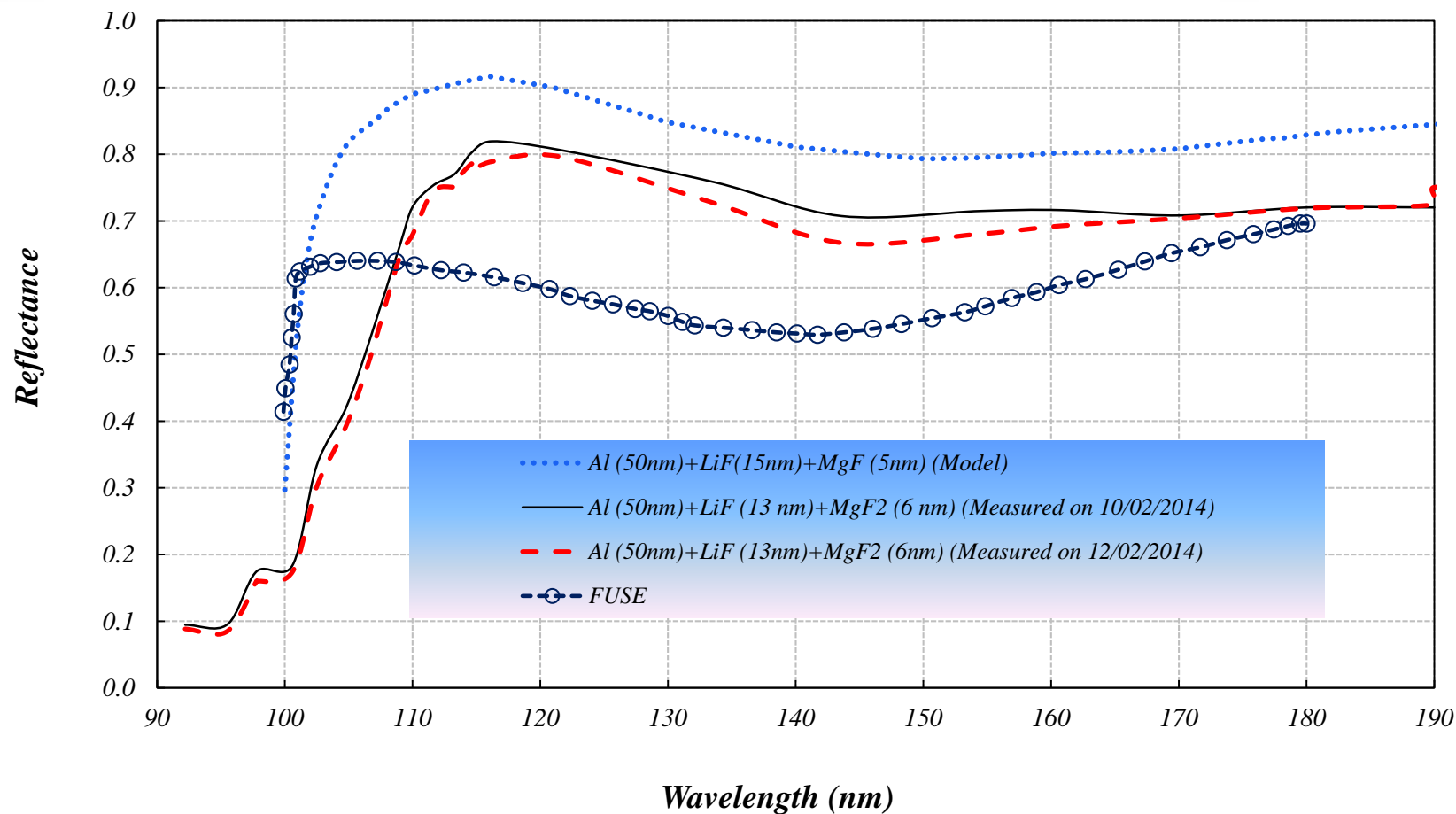
Al+LiF Mirror FUV Predicted Performance



Dual bowl fixture

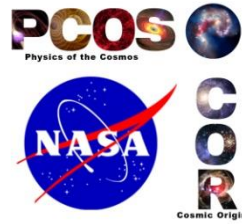


Al/LiF/MgF₂ Test Run



Al/LiF/MgF₂ Coating has been stable over a 2 month period!

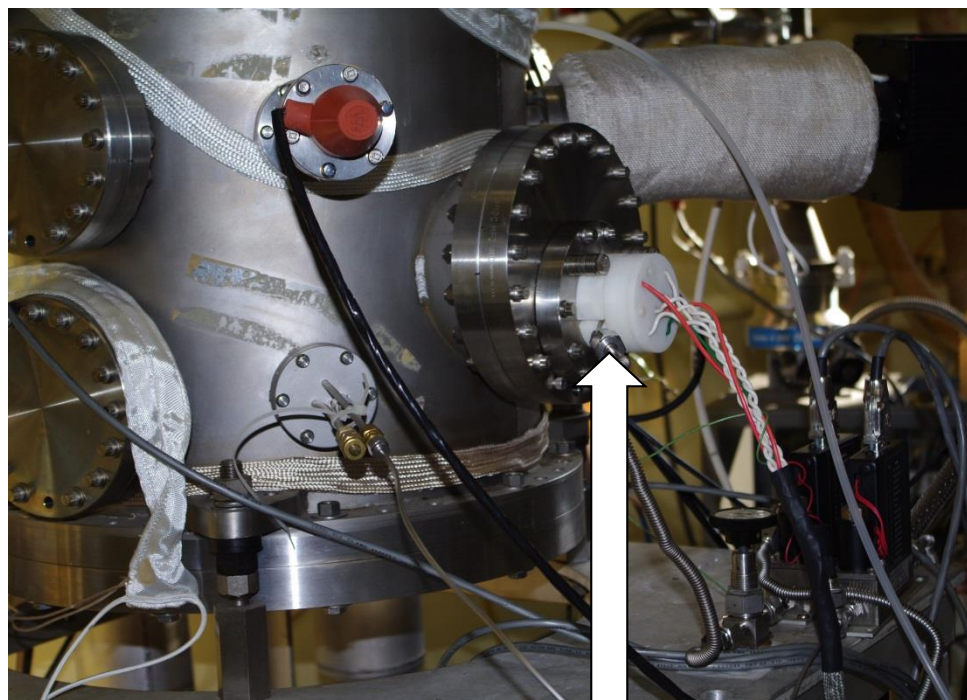
Future Proposed Development



- Develop the capability to use IAPVD (Ion Assited Physical Vapor Deposition) to further enhance UV performance.
- Scale the process for larger optics (i.e. improved uniformity)
- Further develop methods to protect hygroscopic materials.

Ion Beam Sputtering Coating Chamber

- Upgrade chamber with a two-gas flow controller system.
- Krypton gas to be used in the ion-beam sputtering depositions.
- Freon (CF_4) used as reactive gas to replenish the targets (MgF_2) stoichiometry.
- Added heaters to the chamber:
To improve microcrystalline film properties.



Reactive gas intake

Next Generation UV Spectroscopy

- Suborbital Imaging Spectrograph for Transition region Irradiance from Nearby Exoplanet host stars (SISTINE)
 - High-throughput using enhanced LiF GSFC coatings
 - 1st flown sub-arcsecond, medium spectral resolution ($R=10,000$) spectrograph covering 100-160 nm bandpass.

